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# Efficient Intracavity Beam Combining of Multiple Lasers in a Composite Cavity

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## 1. Introduction

High power or high energy solid-state lasers are required in many applications, but are limited in beam quality or brightness at high pump level by thermal effects. Beam combining with two lasers is an effective way to solve this problem and has been successfully realized in the past (Sabourdy et al., 2002; Sabourdy et al., 2003; Qinjun et al., 2005; Eckhouse et al., 2005). In order to get higher output energy with good beam quality, researchers often regard the two-channel combined configuration as the elementary laser and combine an even number of elementary lasers in a tree architecture (Sabourdy et al., 2002; Sabourdy et al., 2003; Qinjun et al., 2005). These direct extending schemes can successfully combine  $2 \times N$  channel lasers into one beam intracavity, but the whole scaling geometry is really complicated and bulk, which bring more difficulties for alignment among multiple branches. Besides all these additions of laser beams are only obtained with spatial Gaussian beams (Sabourdy et al., 2002; Sabourdy et al., 2003; Qinjun et al., 2005), which limits the output power for scaling. Using a planar interferometric coupler, Ishaaya firstly reported intracavity beam addition of transverse multimode laser beam distributions (Ishaaya, et al., 2004), then more than two lasers combination has also been demonstrated (Eckhouse, et al., 2005; Eckhouse, et al., 2006). In these schemes, the thick planar interferometric coupler with a high-precision plane is the key component. But it is difficult to fabricate this coupler, further, the intracavity loss will increase when multiple beams being combined. In addition, most of these more than two-channel combining schemes are based on the open-ended configuration (Sabourdy et al., 2002; Sabourdy et al., 2003; Qinjun et al., 2005; Eckhouse et al., 2005; Eckhouse, et al., 2006; Ishaaya, et al., 2004), if the symmetries of many branches are not well guaranteed, the loss will be unavoidably introduced from every open end of the beam splitter or coupler, consequently resulting in instability of the whole composite cavity. Generally speaking, these kinds of cavities are not very easy to implement at present.

Recently, we have presented a new close-ended Four-Mirror Cavity to combine two beams with two gain media intracavity (Ming & Mali, 2007). Base on this, in this letter, we propose a novel and practical composite-cavity, named Six-Mirror Cavity, to combine four beams with four gain media intracavity. This cavity is based on a close-ended configuration, which makes the output very stable, even when multiple channels combining at the high pump level. Also, it is not the direct extending of the two-channel scheme as the conventional strategies, the

Source: Advances in Solid-State Lasers: Development and Applications, Book edited by: Mikhail Grishin, ISBN 978-953-7619-80-0, pp. 630, February 2010, INTECH, Croatia, downloaded from SCIYO.COM

reduction of two mirrors compared with the scaling scheme shown in Ref (Ming & Mali, 2007), makes the whole scaling configuration simple, compact and easy to implement. Moreover, it is an approach for efficient intra-cavity beam addition of transverse multimode laser beam distributions, possessing considerably more energy than that of Gaussian beam distributions. The whole cavity is composed of several LD pumped laser modules. Compared to end-pumped scheme, the diode-side-pumped configuration has a more excellent scalability to obtain high output energy (Fujikawa et al., 1997). Several side-pumped lasers with slab and rod media geometries were investigated. Slab geometry requires expensive slab-shaped materials, and it is difficult to generate symmetrical beam patterns because of the rectangular cross section of the laser medium (Golla et al., 1995). On the contrary, side-pumped scheme by using rod laser systems can overcome the above-mentioned shortcomings and is especially appropriate for beam combination. Therefore, here we adopt the diode arrays side-pumped rod laser as the basic module and combine four laser modules intracavity with a six-mirror cavity.

## 2. Six-mirror cavity configuration

The basic configuration for energy addition of four lasers with six-mirror cavity is schematically presented in Fig.1. The cavity is based on close-ended resonator, which is composed of six end mirrors  $M_1$ - $M_6$ .  $M_1$ - $M_5$  are flat 100% reflectors at the laser wavelength (1064nm) and  $M_6$  is the output mirror with 80% transmission at 1064nm. Thanks to two 50/50 beam splitters, BS, the lasers produced by each arm combine together into one beam in the end and export from the output coupler  $M_6$ .

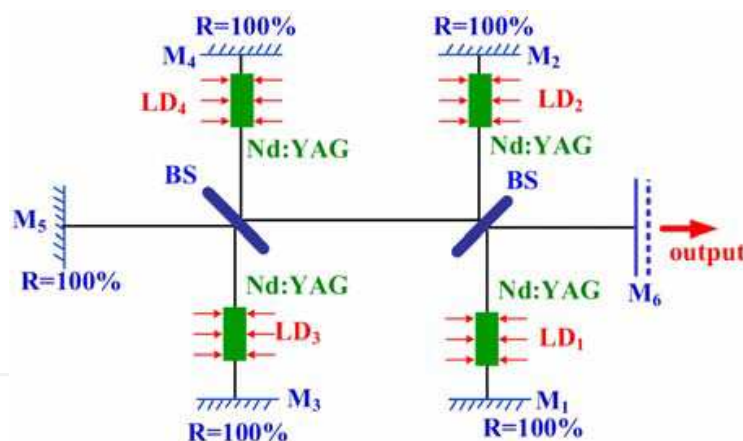


Fig. 1. Schematic of the experimental setup of the six-mirror cavity. BS: beam splitter; LD: laser diode;  $M_1$ - $M_6$ : mirrors;

The whole system consists of four amplifying modules, i.e., four laser heads, arranged in the respective branch arm. Fig.2 shows the schematic cross section of the side-pumped Nd:YAG rod laser head. The laser rod (diameter of 5mm, length of 55mm, Nd-doping level of 1.0 at.%) is placed in a glass tube for direct water cooling. Outside the tube, a number of linear LD arrays are located circular-symmetrically and densely around the rod, generating 808nm laser that is directly coupled into the rod. The two end faces of the rod are AR-coated at 1064nm and wedged into 2 degree, which prevents the self-oscillation of the rod. Each pump LD arrays is directly attached to a copper heat sink. The temperature of the pump modules is controlled by the water flow through the copper heat sinks to regulate the temperature of the diode lasers within an accuracy of  $\pm 0.2^\circ\text{C}$ .

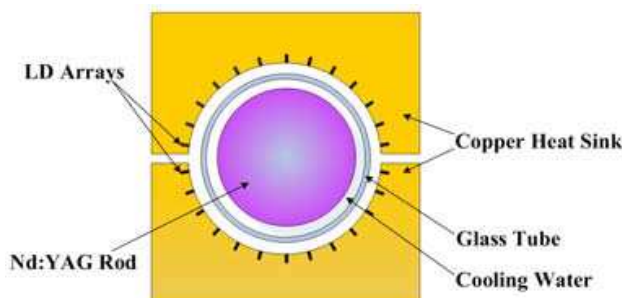


Fig. 2. Schematic cross section of the side-pumped Nd:YAG rod laser head

Every laser head works in a free-running mode and the LD energy supply provides 240μs electric pulse and 1Hz repetition rate. 1μs pulse synchronization has been set among the four channels with the outer-trigger, so that the laser beams produced by every laser heads can be combined temporally and spatially at the same time.

### 3. Experimental results and analysis

We use EPM2000 two-channel joulemeter/power meter and J50HR energy probe (Molelectron, Inc.) to measure the output energy and a laser beam analyzer (Spiricon M<sup>2</sup>-200) to detect the beam quality and the intensity distribution for the combined laser and the four individual lasers. As is illustrated in Fig.3, the output energies of the six-mirror cavity when only one LD arrays (LD<sub>1</sub>, LD<sub>2</sub>, LD<sub>3</sub> or LD<sub>4</sub>) is pumping, and the combined energy when four LD arrays are pumping simultaneously are shown. A single beam multimode output exceeding 453mJ (165μs duration, 1Hz repetition rate) at 1064nm is obtained when the four laser heads work simultaneously in the six-mirror cavity.

In order to demonstrate the improved brightness of six-mirror cavity, four Fabry-Parot lasers with the cavity length of 31cm (same to the length of  $l_2 + l_7$  in Fig.4(b)) are characterized for reference with the experimental setup shown in Fig.4(a). When the four LD arrays, i.e. four laser heads, work at the maximum pump energy of 1.26J with 70A operating current, the output properties in five cases are listed in Table 1 and the brightness is calculated by the expression (Fan, 2005)

$$B = \frac{E}{\lambda^2 \cdot (M_x^2 \cdot M_y^2)} = \frac{k \cdot E}{M_x^2 \cdot M_y^2} \quad (1)$$

where

$$k = 1/\lambda^2 \quad (2)$$

The increasing output energy and the good combined beam quality are well shown in Table 1 and Fig.4. Using this six-mirror cavity, four independent elementary multimode lasers have been successfully combined into one beam intracavity with the combination efficiency of 90.7% ( $453.3/(124.7+131.2+115+128.6)=0.907$ ), a rather high value despite the disparity and multimode distribution among the four branch laser heads features. These results can be explained as follows. In the laser cavity, the four elementary lasers are inter-seeds of each other. One laser beam imprint its transverse distribution content on the other three beam distributions. The combined laser tends to operate so that the losses are minimum. Therefore, each of the transverse beam distribution adds with its counterpart in the other three beams and four multimode beam distributions have similar distribution composition.

Consequently four multimode beams combine intracavity successfully and considerably higher output energy is obtained in laser system. The brightness of the combined laser has been significantly improved more than 3 times compared to single F-P cavity laser. Furthermore, the experiments also show that when the pump energy is fixed, the laser output of the six-mirror cavity is stable with no change in energy or beam quality, which shows that this cavity can withstand environmental perturbations very well.

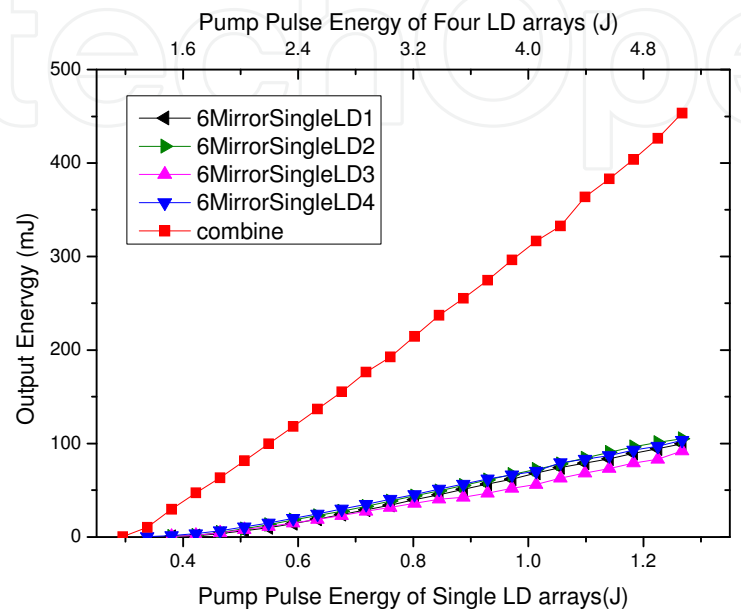
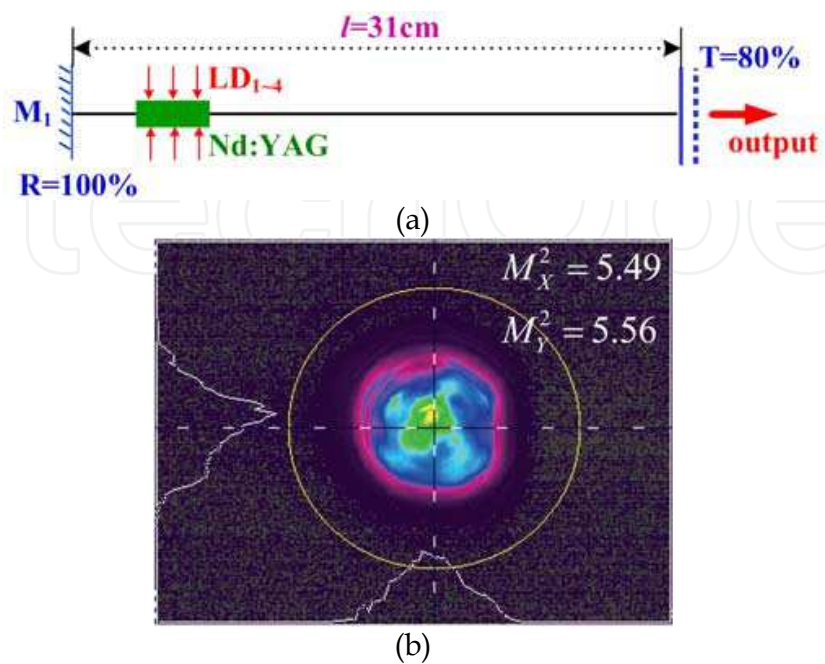


Fig. 3. Dependence of the output energies on the pump energy launched on each LD arrays. The filled triangles with four directions show the output energies of the six-mirror cavity when only one LD arrays(LD1,LD2,LD3 or LD4) is pumping respectively; The filled triangles show the output energies of the six-mirror cavity when LD1~LD4 are pumping simultaneously with the pump energy at the top.





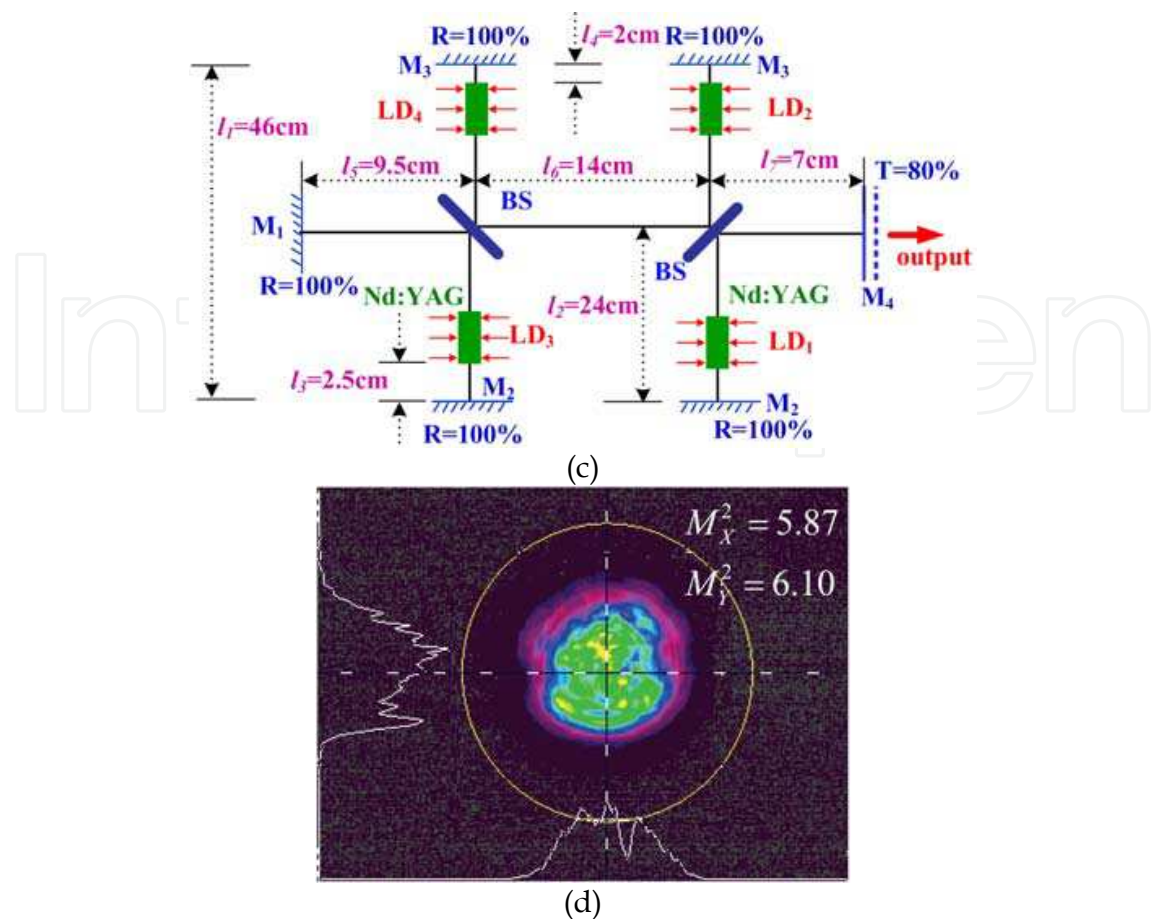


Fig. 4. The setup of Fabry-Parot cavity and six-mirror cavity and the detected output intensity distributions at the maximum pump energy

(a) The setup of the Fabry-Parot cavity laser

(b) The intensity distributions of the Fabry-Parot cavity laser with individual LD<sub>1</sub> arrays pumping

(c) The setup of six-mirror cavity laser

(d) The intensity distribution of the six-mirror cavity laser with four LD arrays pumping simultaneously

4. Conclusion

A new laser scheme for energy scaling with a composite six-mirror cavity is demonstrated. Unlike the conventional method that directly extends the two-beam addition configuration to 2×N channels geometry in a tree architecture, in this paper, we present a new close-ended six-mirror cavity, which is more compact, stable and practical, to combine four multimode laser beams intracavity. The combined output characteristics including energy, beam quality and the improved brightness of this laser are investigated experimentally. The results demonstrate that four multimode individual Nd:YAG lasers have been combined intracavity successfully with this six-mirror cavity, and a single beam laser output exceeding 453mJ with 165μs duration is achieved, with 90.7% combining efficiency. The brightness of the combined laser has been significantly improved compared to single F-P cavity laser. In conclusion, the use of this six-mirror cavity provides a novel approach for the efficient improvement of brightness and energy scaling by combination of multiple lasers.

Parameter	Pump current	Pump Energy	Output energy	Beam quality		Calculated Brightness <i>mJ / (m<sup>2</sup> · ster)</i>
				$M_x^2$	$M_y^2$	
F-P1	70A	1.26 J	124.7 mJ	5.49	5.56	4.08k
F-P2		1.26 J	131.2 mJ	5.62	5.97	3.91k
F-P3		1.26 J	115 mJ	5.24	5.66	3.87k
F-P4		1.26 J	128.6 mJ	5.37	5.78	4.14k
Six-mirror combined	70A	1.26J+1.26J +1.26J+1.26J	453.3 mJ	<b>5.87</b>	<b>6.10</b>	<b>12.66k</b>

Table 1. The output properties in five cases at the maximum pump energy  
k: coefficient. F-P1: The Fabry-Perot cavity laser with LD<sub>1</sub> arrays pumping  
F-P2: The Fabry-Perot cavity laser with LD<sub>2</sub> arrays pumping  
F-P3: The Fabry-Perot cavity laser with LD<sub>3</sub> arrays pumping  
F-P4: The Fabry-Perot cavity laser with LD<sub>4</sub> arrays pumping  
Six-mirror combined: The Six-mirror cavity laser with LD<sub>1</sub>, LD<sub>2</sub>, LD<sub>3</sub> and LD<sub>4</sub> arrays pumping simultaneously

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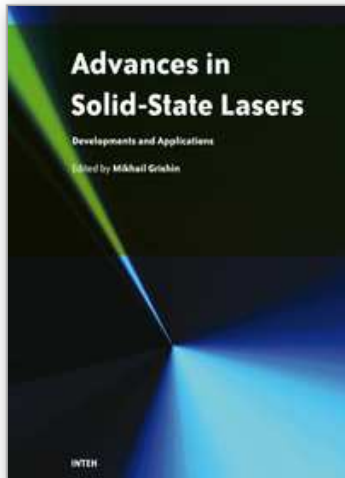
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## **Advances in Solid State Lasers Development and Applications**

Edited by Mikhail Grishin

ISBN 978-953-7619-80-0

Hard cover, 630 pages

**Publisher** InTech

**Published online** 01, February, 2010

**Published in print edition** February, 2010

Invention of the solid-state laser has initiated the beginning of the laser era. Performance of solid-state lasers improved amazingly during five decades. Nowadays, solid-state lasers remain one of the most rapidly developing branches of laser science and become an increasingly important tool for modern technology. This book represents a selection of chapters exhibiting various investigation directions in the field of solid-state lasers and the cutting edge of related applications. The materials are contributed by leading researchers and each chapter represents a comprehensive study reflecting advances in modern laser physics. Considered topics are intended to meet the needs of both specialists in laser system design and those who use laser techniques in fundamental science and applied research. This book is the result of efforts of experts from different countries. I would like to acknowledge the authors for their contribution to the book. I also wish to acknowledge Vedran Kordic for indispensable technical assistance in the book preparation and publishing.

### **How to reference**

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Ming Lei (2010). Efficient Intracavity Beam Combining of Multiple Lasers in a Composite Cavity, *Advances in Solid State Lasers Development and Applications*, Mikhail Grishin (Ed.), ISBN: 978-953-7619-80-0, InTech, Available from: <http://www.intechopen.com/books/advances-in-solid-state-lasers-development-and-applications/efficient-intracavity-beam-combining-of-multiple-lasers-in-a-composite-cavity>

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